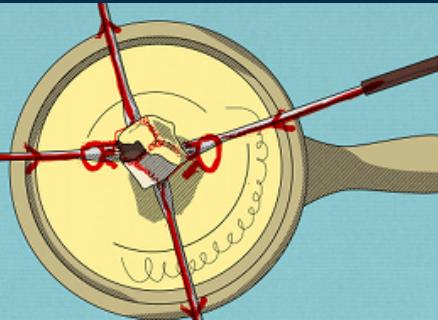


# QCD@LHC

22<sup>ND</sup>-26<sup>TH</sup> AUGUST

INTERNATIONAL CONFERENCE ZURICH

2016



## Search for BSM decays of SM Higgs and non-resonant di-Higgs results in ATLAS and CMS experiments

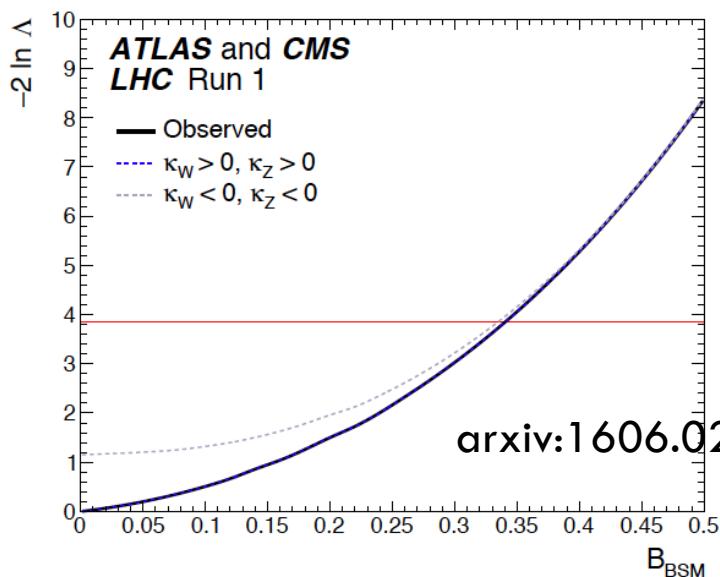
Cong GENG  
Uni. of Michigan/USTC

On behalf of ATLAS and CMS collaborations

# Outline

- Current constraints leave room for BSM physics:

$\text{Br}(\text{H} \rightarrow \text{BSM}) < 34\% \text{ at } 95\% \text{ CL}$



This talk will cover the following topics:

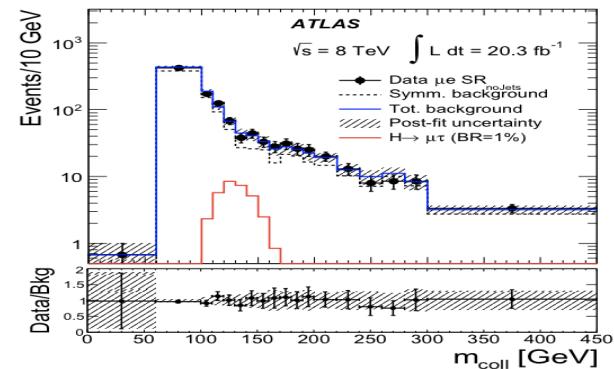
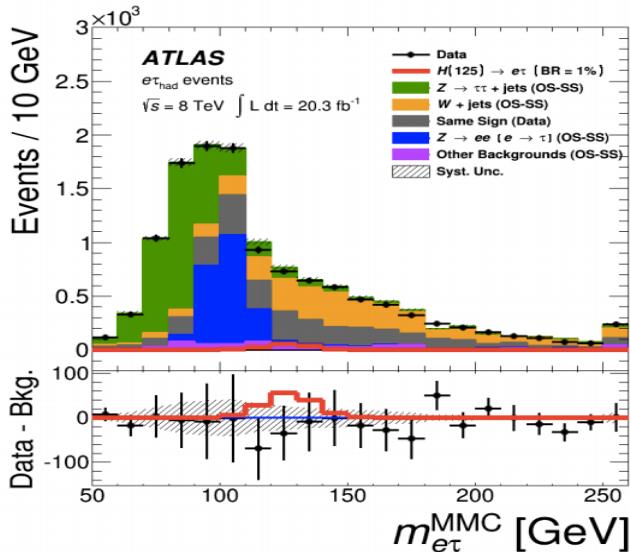
- ◆ Lepton Flavor violation (LFV) in SM Higgs decay
- ◆ Search for NMSSM particle
- ◆ Search for  $\text{H} \rightarrow \text{invisible}$
- ◆ Non-resonant di-Higgs results

# LFV in Higgs decay in ATLAS

3

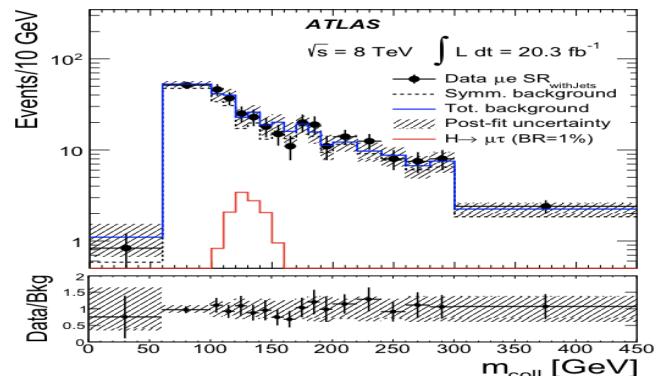
- $H \rightarrow e\tau_{\text{had}}$ ,
  - ❖ OS: electron,  $e\tau_{\text{had}}$ , and  $E_T^{\text{Miss}}$
  - ❖ Two signal regions based on  $m_T$
  - ❖ Distribution of interest: missing mass calculator(MMC)

[arXiv:1604.07730](https://arxiv.org/abs/1604.07730)



- $H \rightarrow e\tau_{\text{lep}}/\mu\tau_{\text{lep}}$ 
  - ❖ OS: one electron, one muon
  - ❖ Two signal regions: no jets and with jets

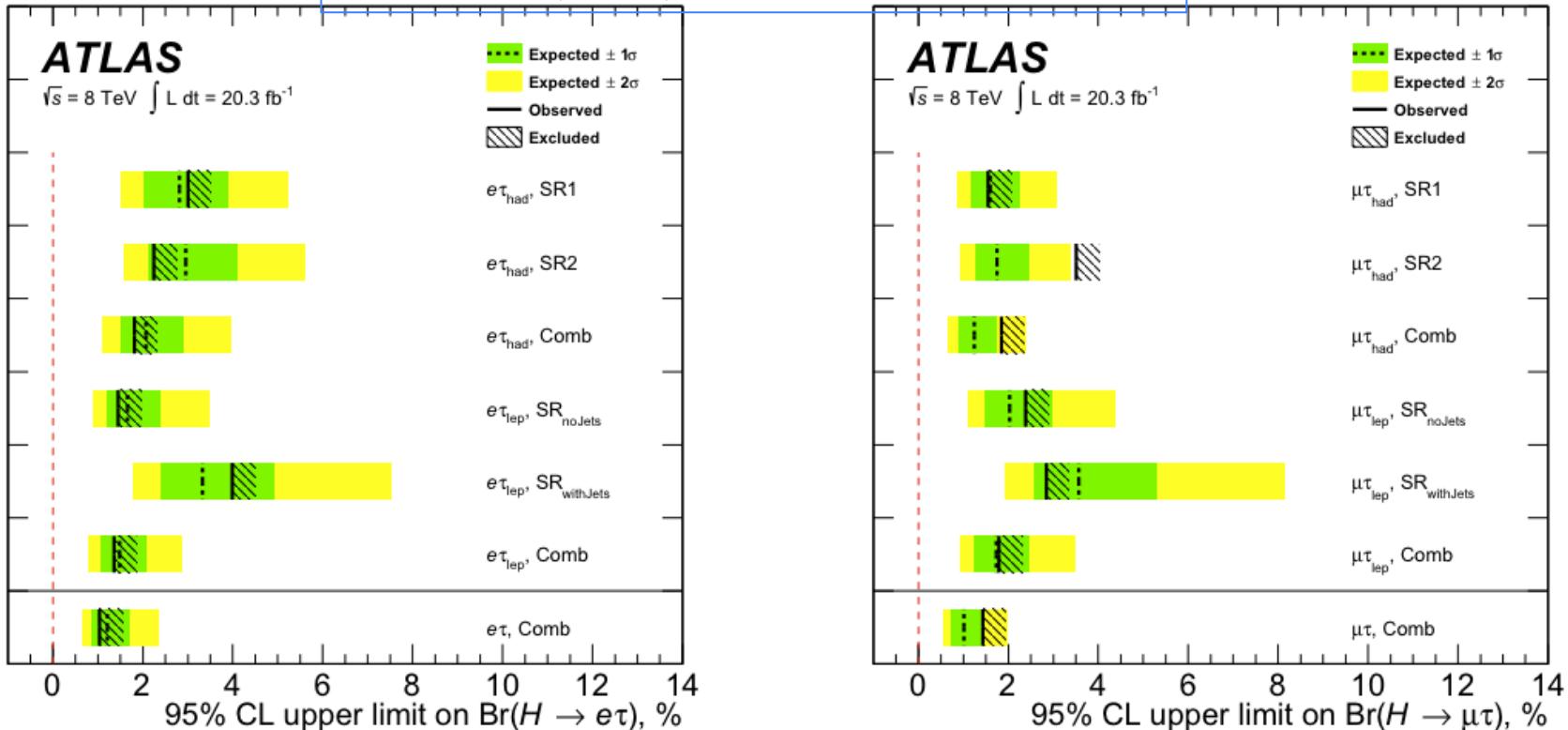
$$m_{\text{coll}} = \sqrt{2p_T^{\ell_1} (p_T^{\ell_2} + E_T^{\text{miss}}) (\cosh \Delta\eta - \cos \Delta\phi)}.$$



# Upper limits on $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ from ATLAS

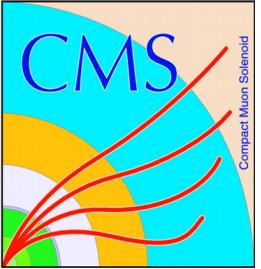
4

JHEP 1511 (2015) 211; arXiv:1604.07730



95% CL upper limit    Observed    Expected

$H \rightarrow e\tau$	1.04%	$1.21^{+0.49}_{-0.34}\%$
$H \rightarrow \mu\tau$	1.43%	$1.01^{+0.40}_{-0.29}\%$

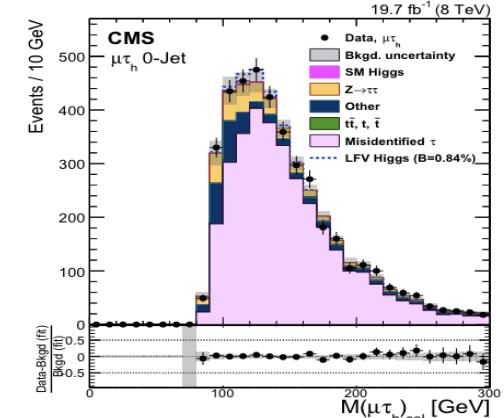
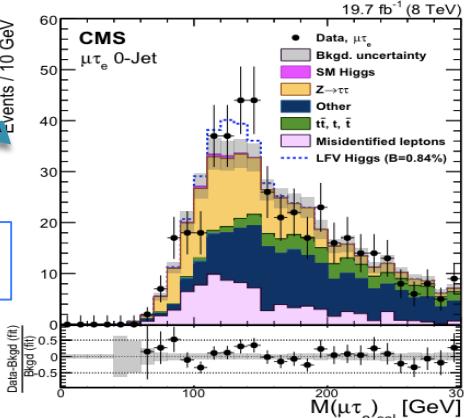
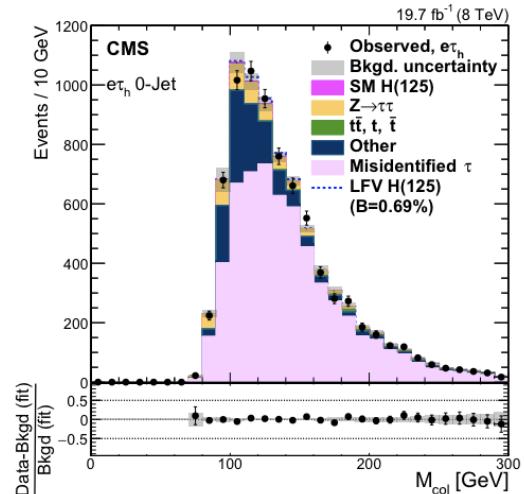
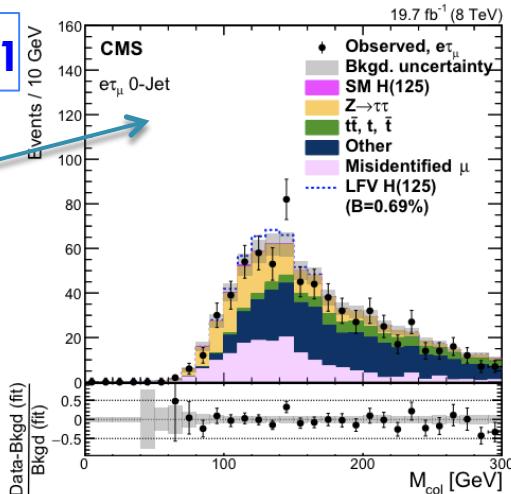


5

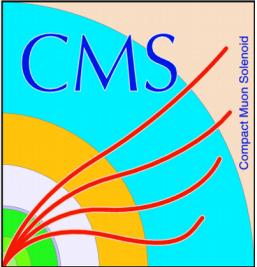
# LFV in Higgs decay in CMS

[arXiv:1607.03561](https://arxiv.org/abs/1607.03561)

- $H \rightarrow e\tau$  and  $\mu\tau$ 
  - ❖ 2 channels: lepton and hadron
  - ❖ 3 categories: 0, 1, and 2 jets
  - ❖ Template fit to the collinear mass spectra

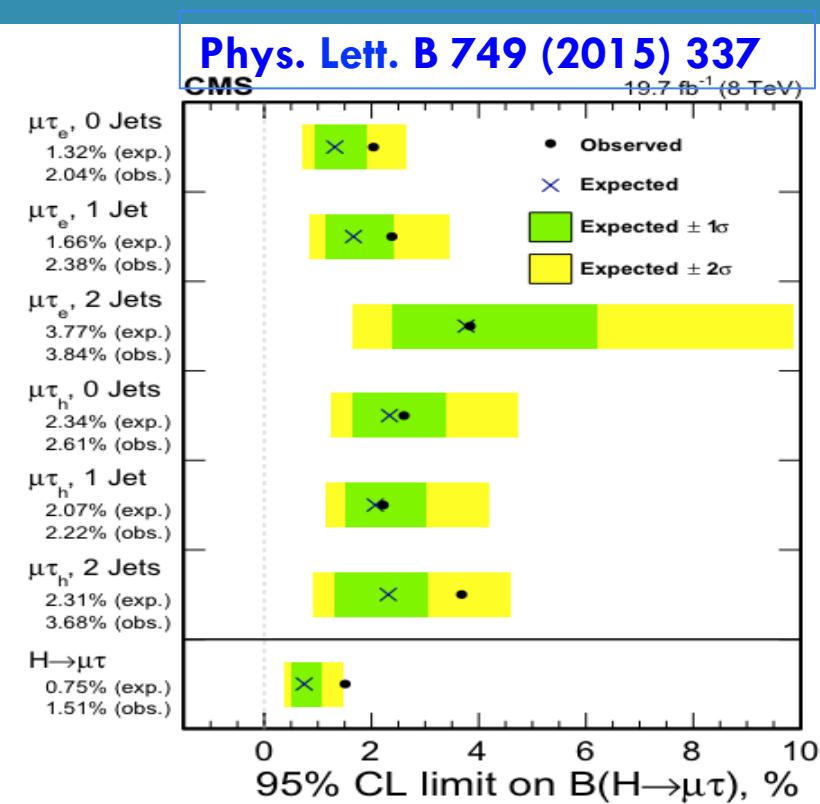
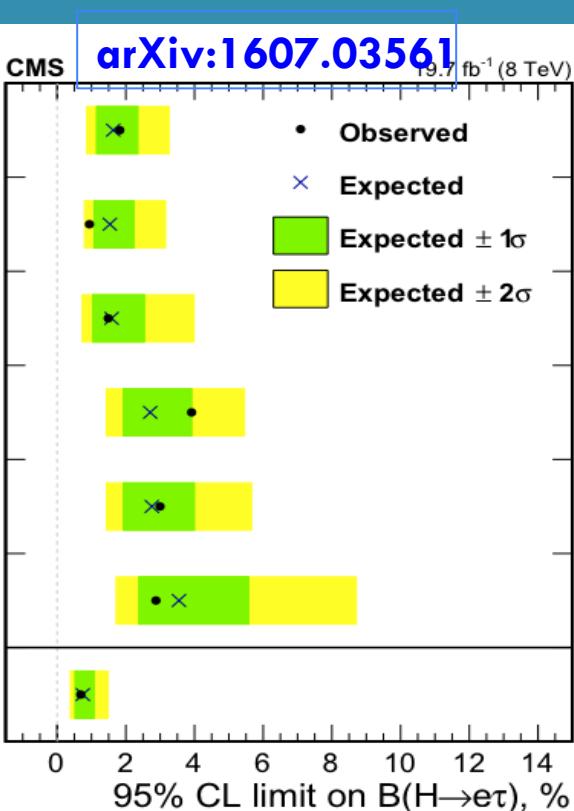


[Phys. Lett. B 749 \(2015\) 337](https://doi.org/10.1016/j.physlettb.2015.06.037)

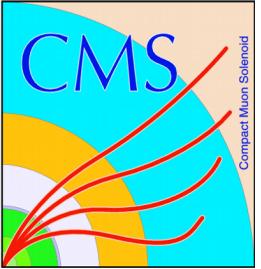


6

# Upper limits on $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ from CMS

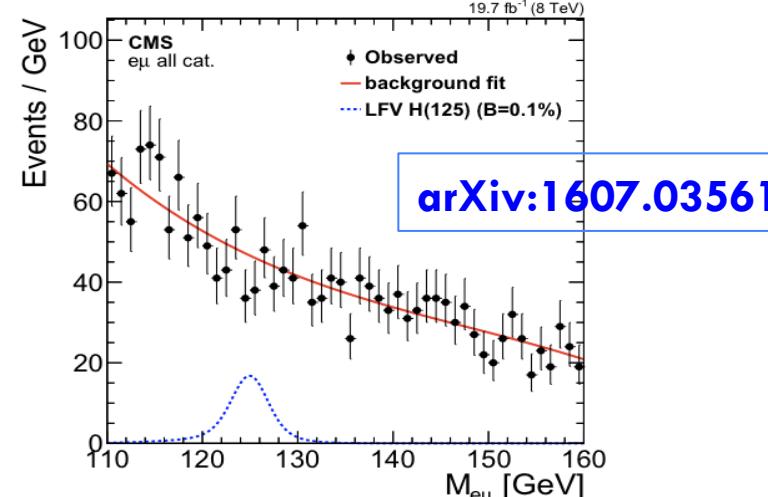
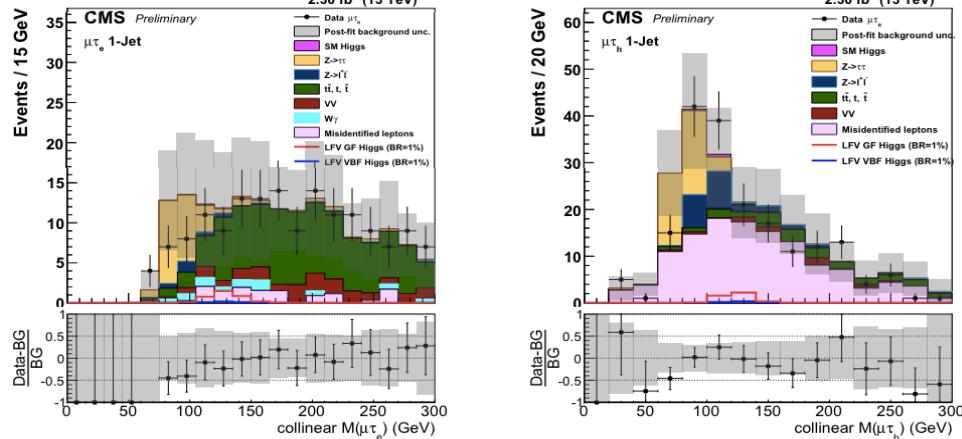
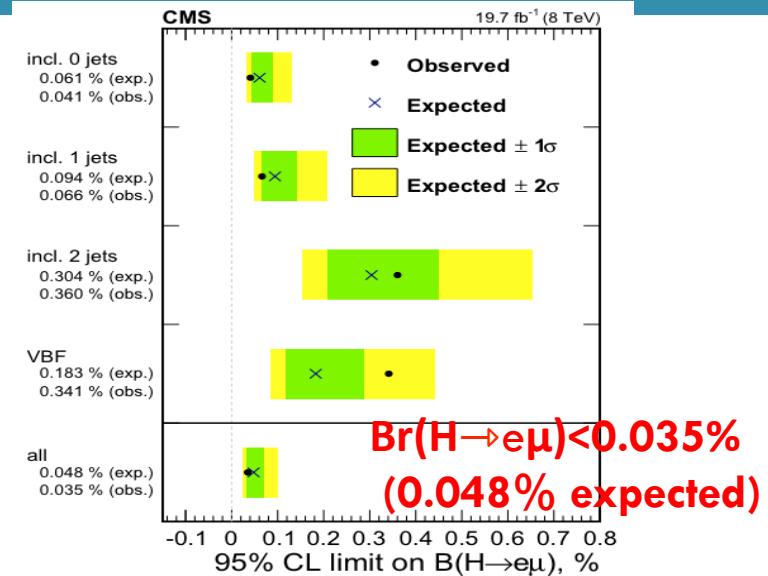
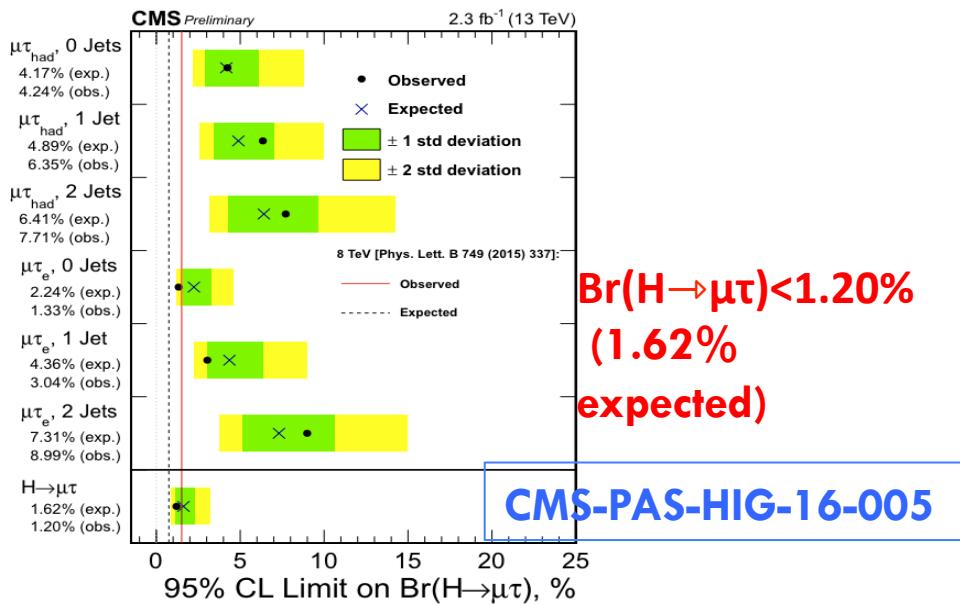


95% CL upper limit	Observed	Expected
$H \rightarrow e\tau$	0.69%	$0.75^{+0.32}_{-0.22}\%$
$H \rightarrow \mu\tau$	1.51 %	$0.75 \pm 0.38\%$



# First look at 13TeV dataset for $H \rightarrow \mu\tau$ and $H \rightarrow e\mu$ with 8TeV dataset

7



# NMSSM

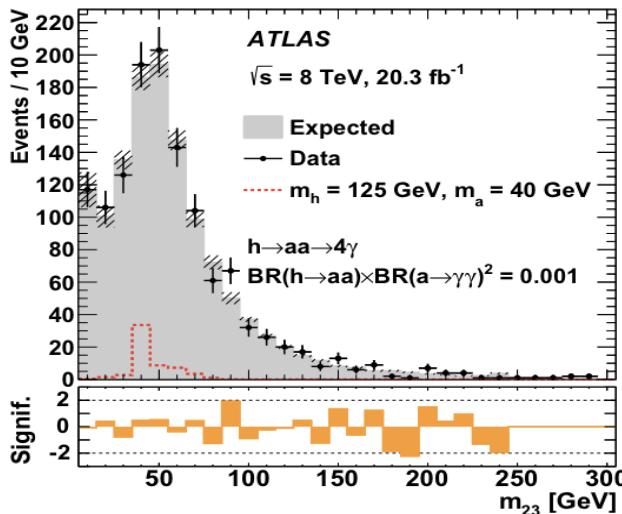
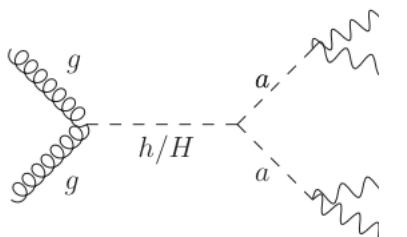
8

- Modified and extended Higgs sectors have been predicted. Possibly additional low mass ( $< 125\text{GeV}$ ) scalars/pseudoscalars exist.
- NMSSM: next-to-MSSM
  - ❖ 2 Higgs doublets + 1 complex singlet  $\rightarrow$  7 Higgs
  - ❖ Compatible with a 125 GeV SM-like scalar ...
- One probe: search for pair production of the light Higgs boson in SM Higgs decays.

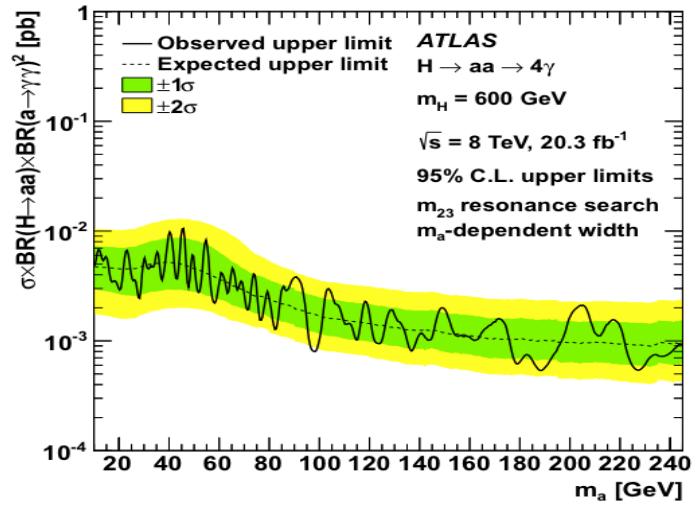
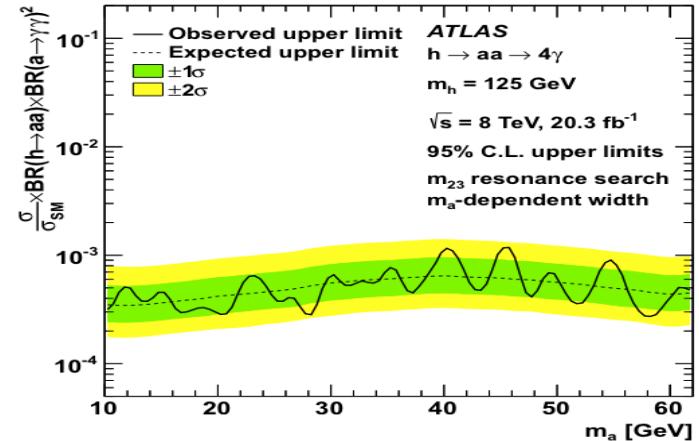
# $h \rightarrow aa \rightarrow 4\gamma$ in ATLAS

9

- Inclusive three photon search interpreted in NMSSM context for  $10 < m_a < 62$  GeV
  - ❖ Select three tight and isolated photons
- Search for excesses in diphoton invariant mass
- Limits on  $(\sigma/\sigma_{SM}) \times BR(h \rightarrow aa) \times BR(a \rightarrow \gamma\gamma)^2$  are obtained for SM Higgs(125 GeV) and for heavier scalars with  $h(H) \rightarrow aa$ .



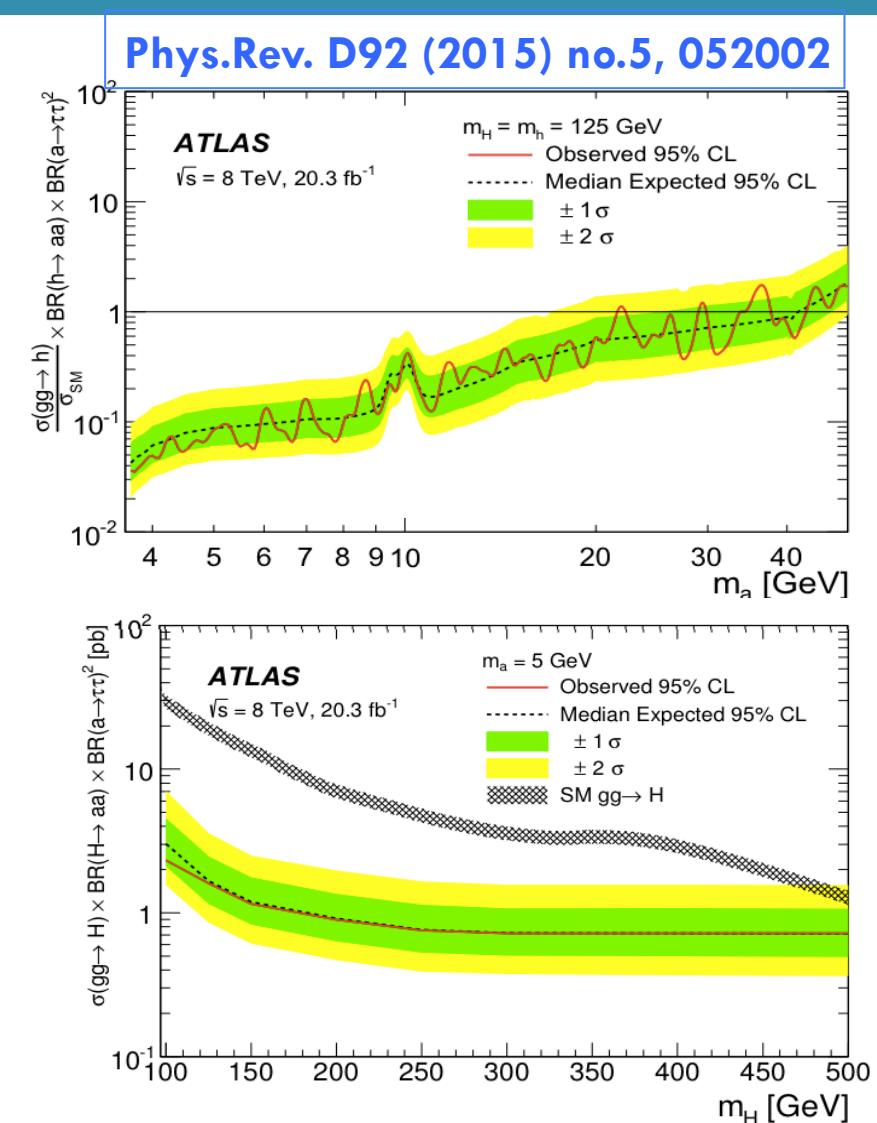
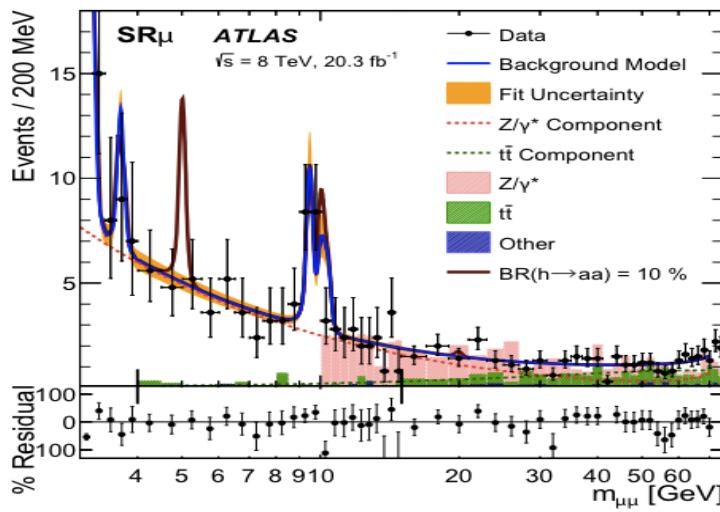
Eur. Phys. J. C (2016) 76: 210



# $h \rightarrow aa \rightarrow \mu\mu\tau\tau$ in ATLAS

10

- Search for a pair of pseudoscalars with masses **3.7-50 GeV**, and for heavy scalar  **$m=100-500$  GeV** decaying to a pair of pseudoscalars with a mass of **5 GeV**
- Selection
  - $a \rightarrow \mu\mu$ : Two high pT OS muons
  - $a \rightarrow \tau\tau$  : 1 e or  $\mu$  and 1 or three tracks ( $e, \mu, \tau_{had}$ )



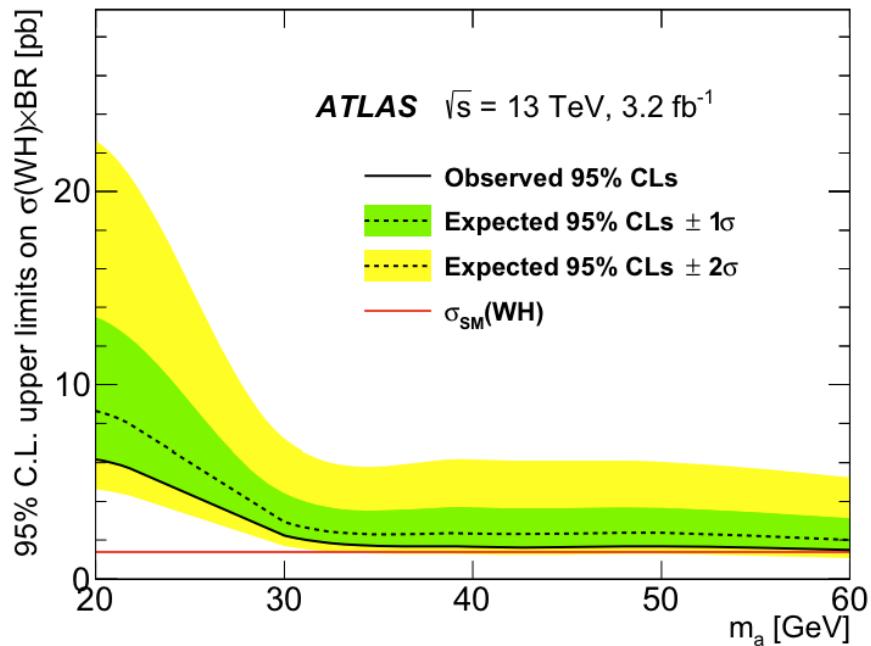
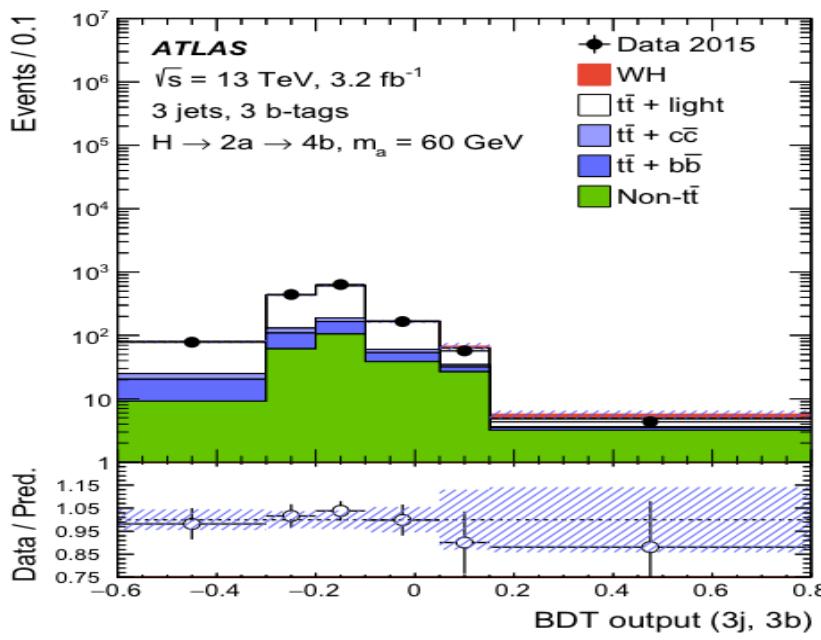
# $Wh \rightarrow Waa \rightarrow lv bbbb$ in ATLAS

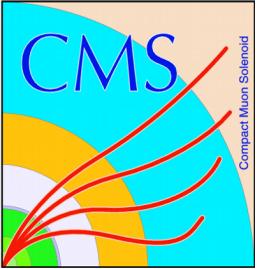
13TeV,  
New

11

[arXiv:1606.08391, Submitted to EPJC](https://arxiv.org/abs/1606.08391)

- ❑ Associated production with a W boson
- ❑ SM-like Higgs boson decays to a pair of pseudoscalars with mass 20-60 GeV
  - ❖ Events with one isolated lepton and at least three jets, with at least two b-jets
- ❑ BDT is used in signal regions.
- ❑ The observed (expected) 95% CL upper limits range from 6.2 (8.6) pb ( $m_a = 20$  GeV) to 1.5 (2.0) pb ( $m_a = 60$  GeV)



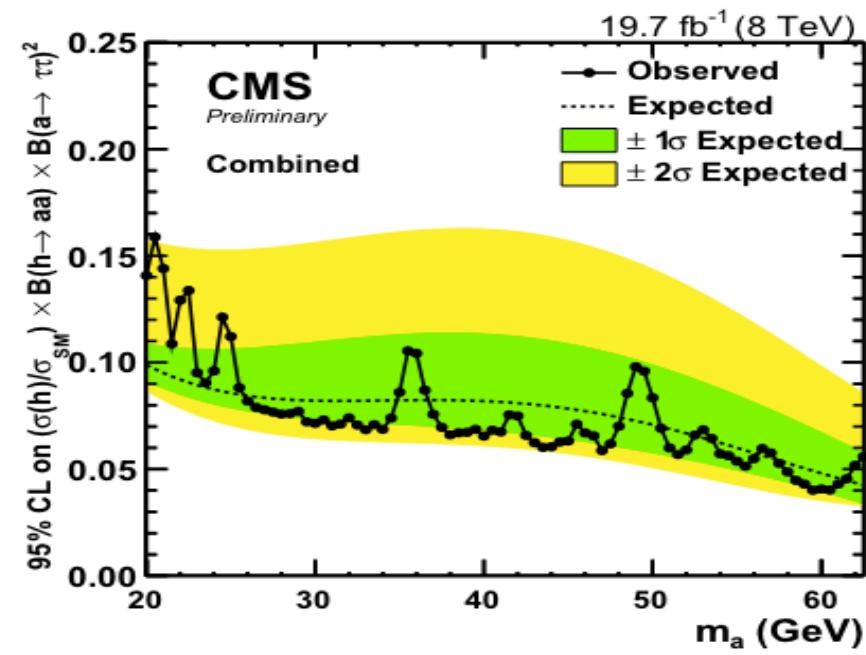
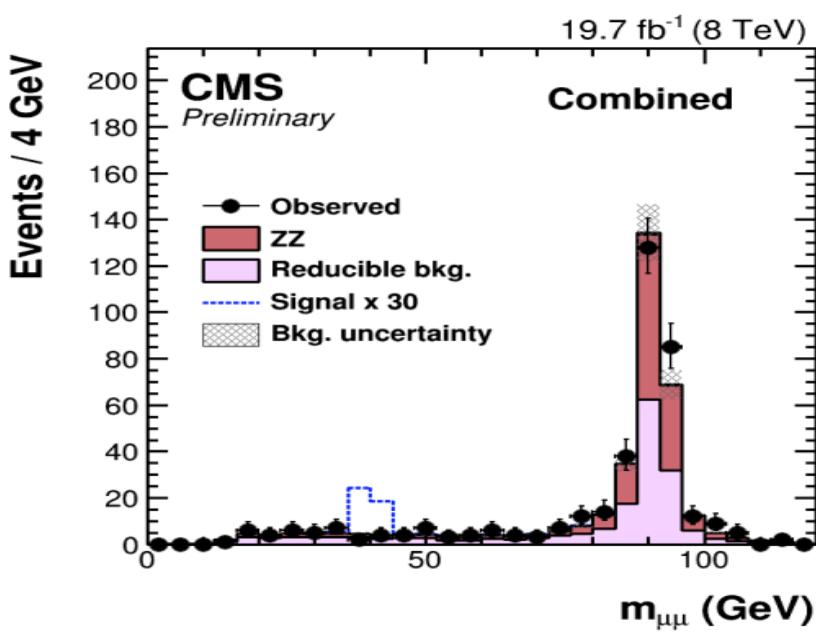


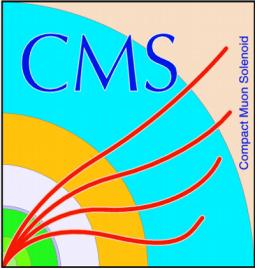
12

# $h \rightarrow aa \rightarrow \mu\mu\tau\tau$ in CMS

CMS-PAS-HIG-15-011

- Categories depend on the tau decay mode ( $e, \mu, \tau_{had}$ )
- Signal discrimination through a fit to the dimu mass distributions.



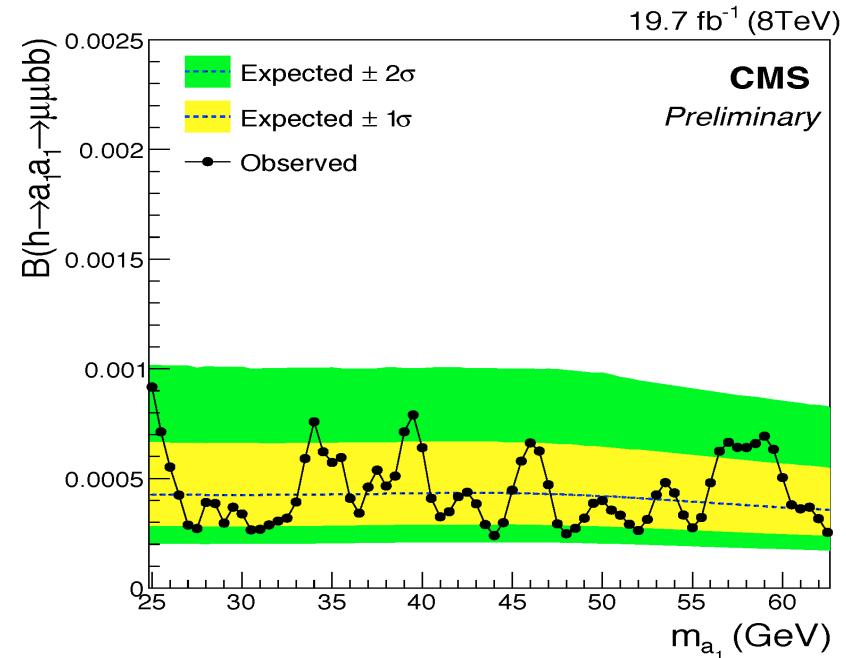
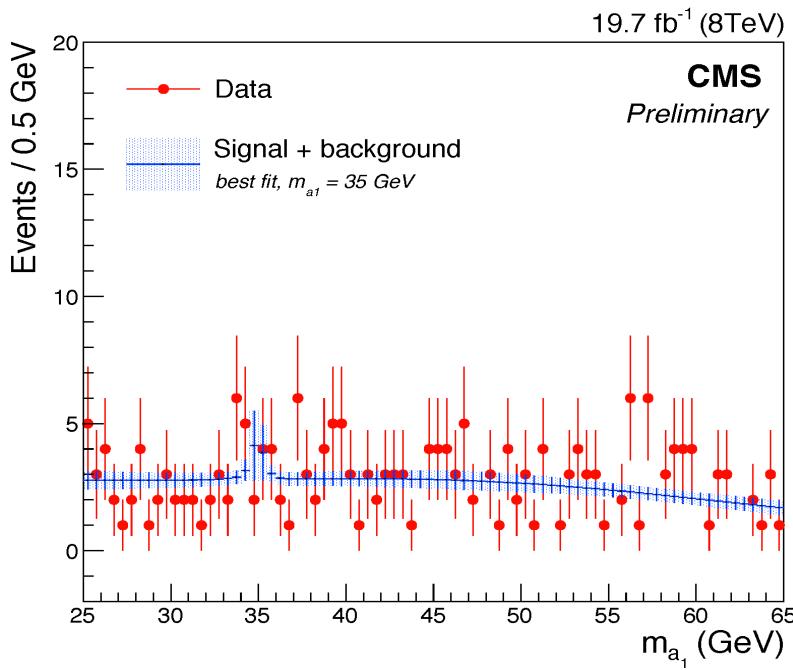


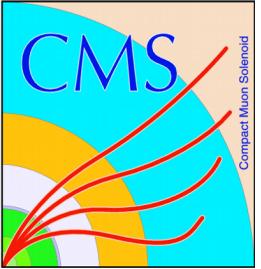
13

# $h \rightarrow aa \rightarrow \mu\mu bb$ in CMS

CMS-PAS-HIG-14-041

- ❑ Signal discrimination through a fit to the dimu mass distributions.
- ❑ Focus on a NMSSM interpretation



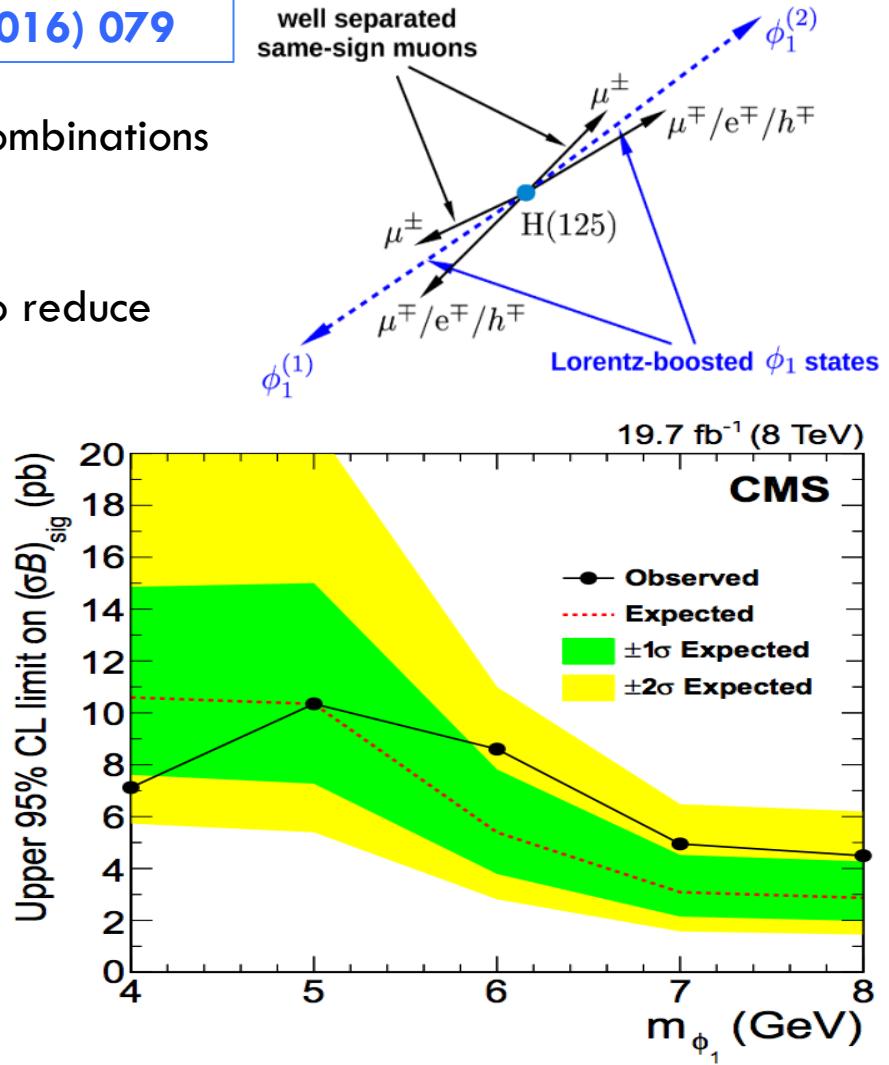
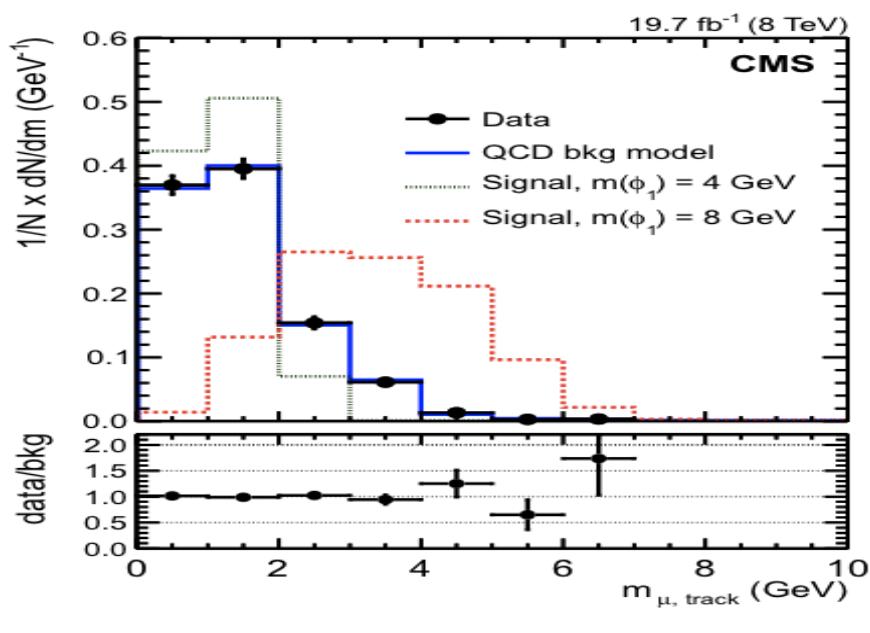


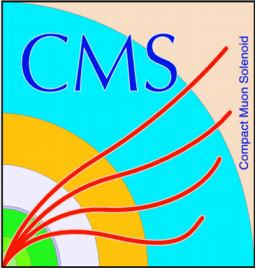
14

# $h \rightarrow aa \rightarrow 4\tau$ ( $I$ ) in CMS

CMS-HIG-14-019; JHEP 01 (2016) 079

- Mass discrimination through muon+track combinations to target a low mass range: 4-8 GeV
- Exploit the presence of same sign muons to reduce background contributions



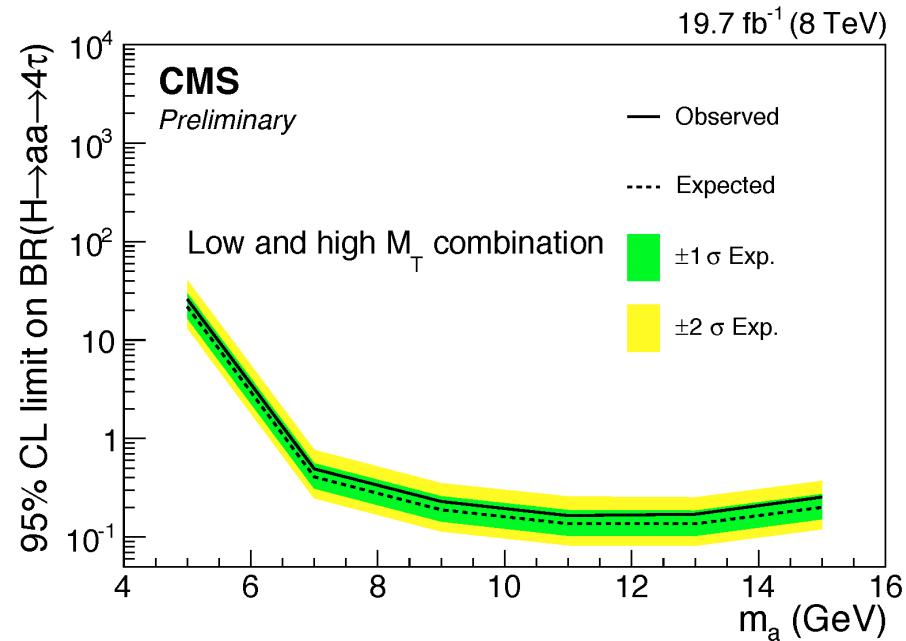
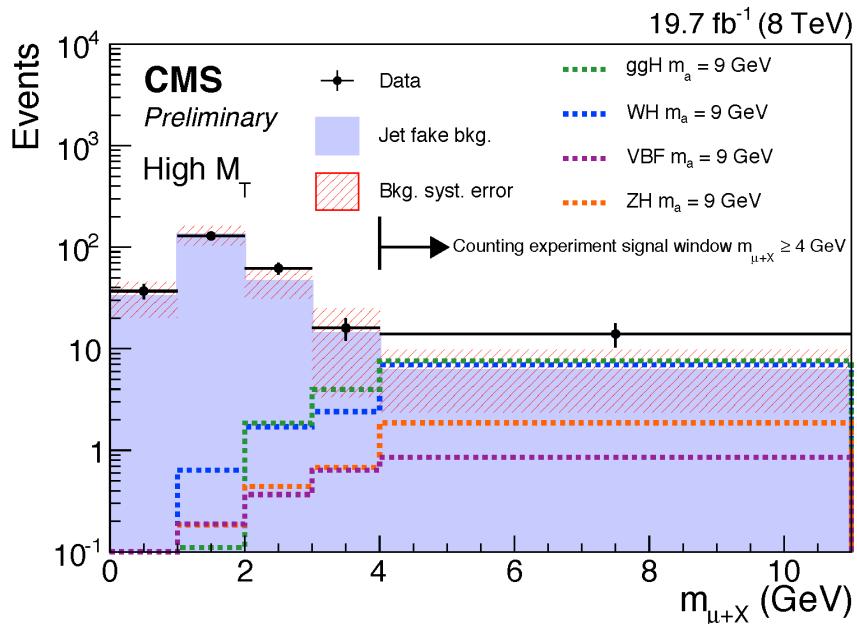
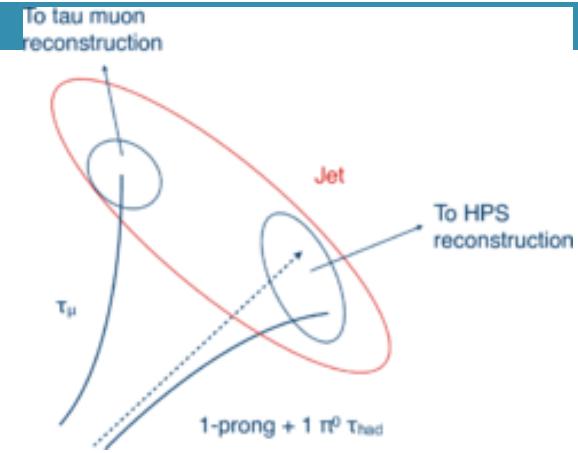


15

# $h \rightarrow aa \rightarrow 4\tau$ (II) in CMS

CMS-PAS-HIG-14-022

- Higher mass range covered (5-15 GeV), can look for hadronic taus (Muon+Hadronic tau combinations)
- Two categories in  $M_T$ 
  - ❖ Low mass targets ggF and VBF production
  - ❖ High  $M_T$  target WH production.



# $H \rightarrow$ invisible

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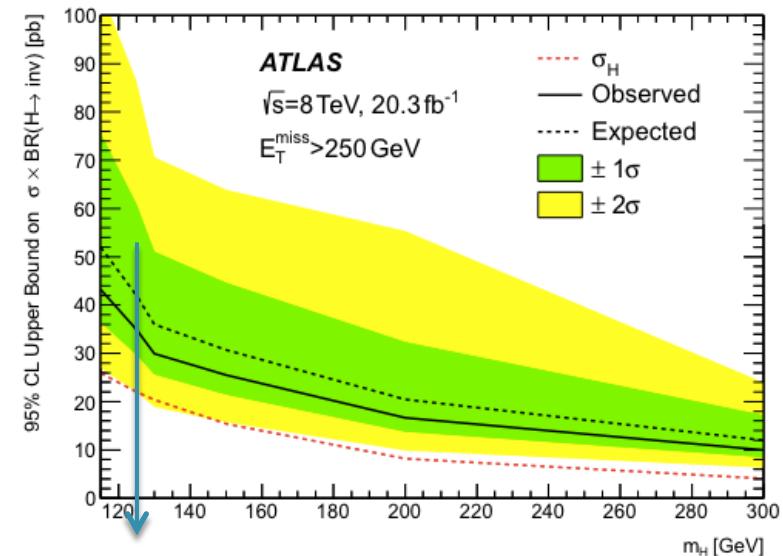
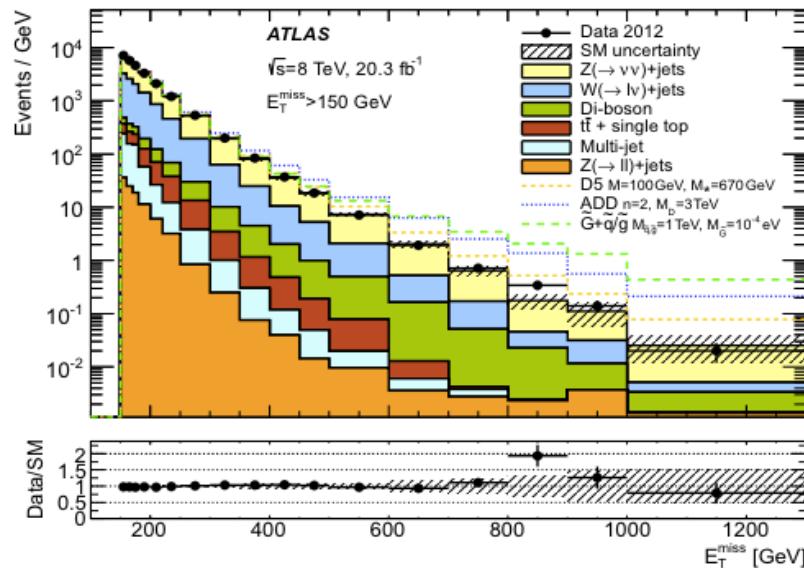
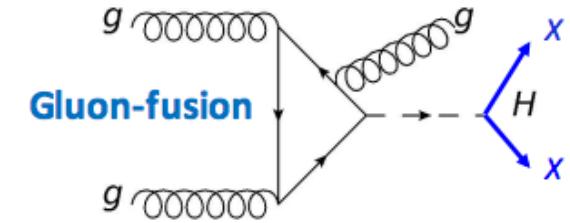
- Production modes
  - ❖ Gluon fusion (ggF): Tag events with an ISR jet
  - ❖ Vector boson fusion (VBF): two well separated jets
  - ❖ Associated production with a boson: tag events through leptons or jets from the boson.
  
- Experimental signature:
  - ❖ Large missing transverse momentum in the event.

# H $\rightarrow$ invisible: ggF in ATLAS

17

Eur. Phys. J. C (2015) 75:299

- Large  $E_T^{\text{miss}} > 150 \text{ GeV}$ , Leading jet  $pT > 120 \text{ GeV}$
- $\Delta\Phi(\text{jet}, E_T^{\text{miss}}) > 1.0$ : suppress the multi-jets background
- Dominant background:  $Z \rightarrow \nu\nu + \text{jets}$  and  $W + \text{jets}$
- Dominant uncertainties: jet and  $E_T^{\text{miss}}$  energy scale and resolution.
- @125GeV,  $(\sigma \times \text{BR})_{\text{obs}} < 1.59 \times \text{SM\_pre}$ ; SM predicted:  $< 1.91 \times \text{SM\_pre}$



# H $\rightarrow$ invisible: VBF and V(jj)H in ATLAS

18

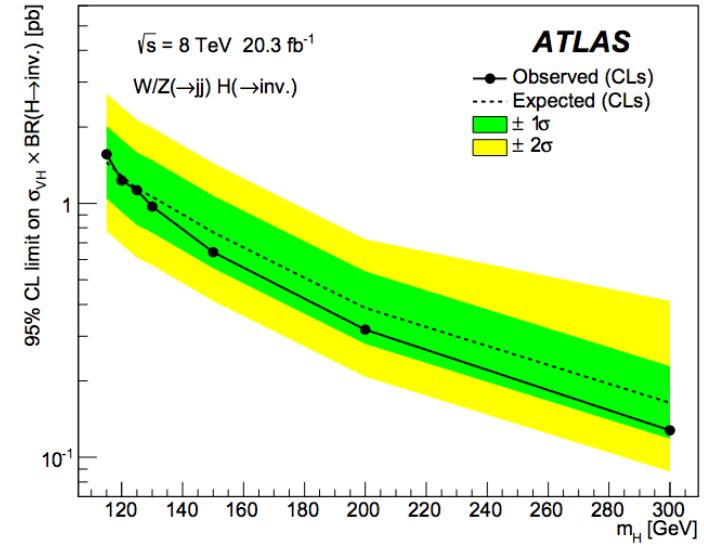
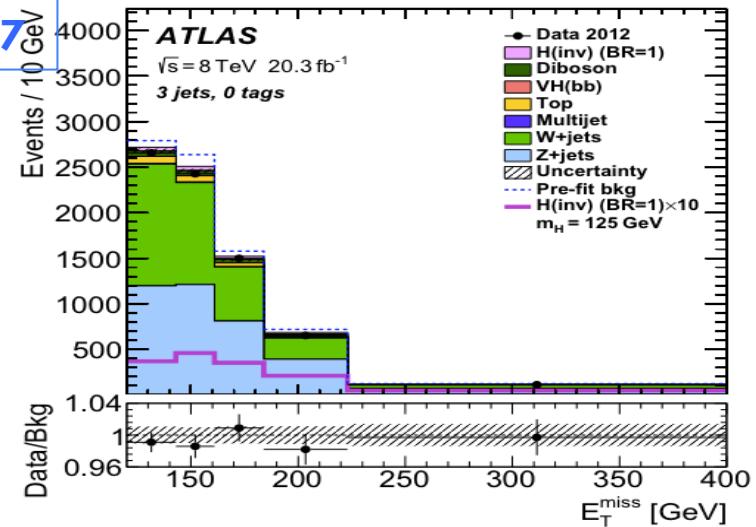
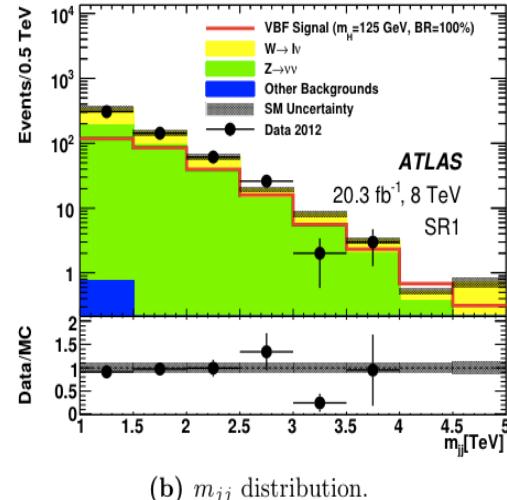
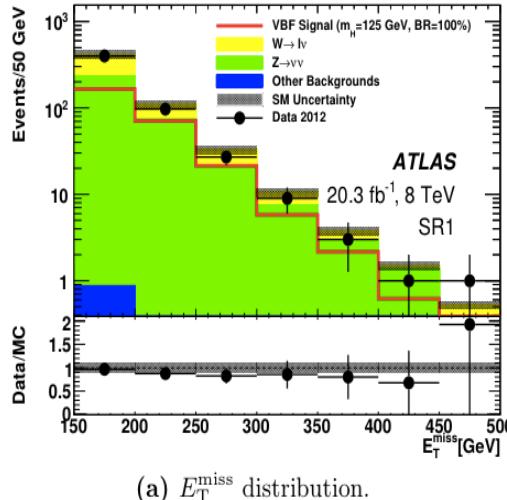
JHEP 01 (2016) 172; Eur. Phys. J. C (2015) 75: 337

## VBF

- Large  $E_T^{\text{miss}} > 150 \text{ GeV}$ , two high-pT jets
- Large jets separation  $|\Delta\eta_{jj}|$ , large dijet mass  $M_{jj}$ 
  - ❖ Different signal regions with different  $\Delta\eta_{jj}$  and  $M_{jj}$
- Derived 95% CL upper limit on BR(H $\rightarrow$ invisible)
  - ❖ @125 GeV,  $\text{BR}_{\text{obs}} < 28\%$ , expected  $< 31\%$

## V(jj)H

- $E_T^{\text{miss}} > 120 \text{ GeV}$ , 2/3 jets;  $M_{jj} \sim M_{W/Z}$ ,  $\Delta R_{jj} \sim$  boosted V-boson
- 95% CL upper limit on  $\sigma_{VH} \times \text{BR}(H \rightarrow \text{invisible})$ : 1.1 pb observed (1.1 pb expected.)
- 95% CL upper limit on BR(H $\rightarrow$ invisible), combine VH and ggF: obs < 78%, exp < 86%

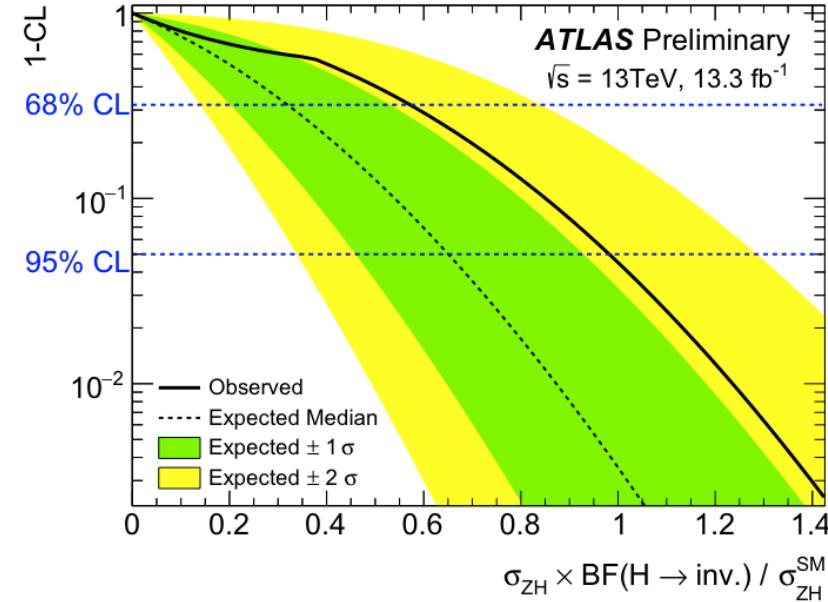
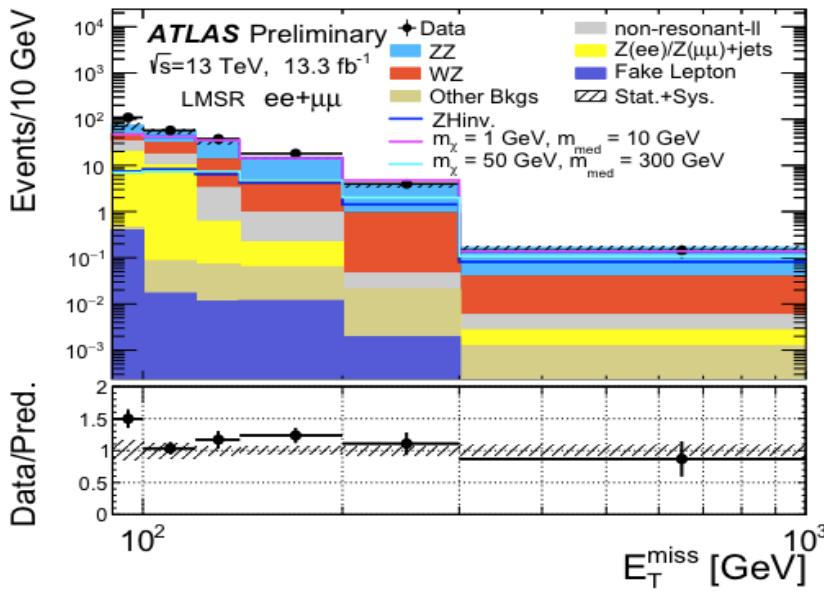


# H $\rightarrow$ invisible: Z(11)H in ATLAS

19

ATLAS-CONF-2016-056

- $E_T^{\text{miss}} > 90 \text{ GeV}$ , exact two isolation leptons
- Looking for events with balance between Z and  $E_T^{\text{miss}}$
- Dominant background: leptonic decays of ZZ and WZ
- 95% CL upper limit on  $\text{BR}(H \rightarrow \text{invisible})$ : obs <98%, exp < 65%**



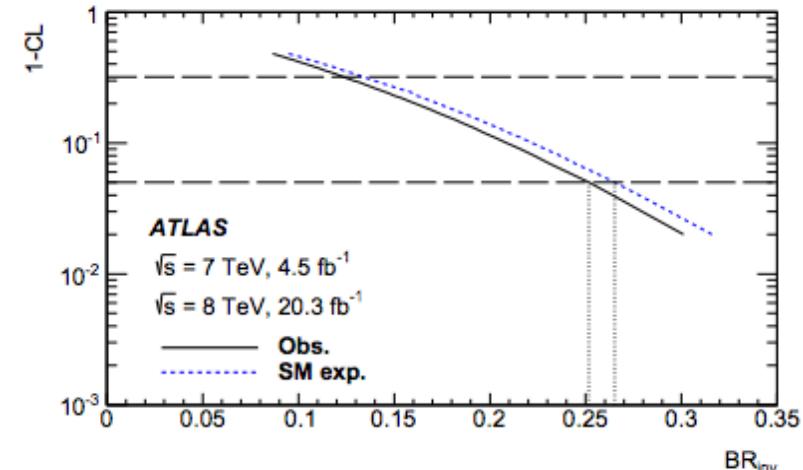
# H $\rightarrow$ invisible: 8TeV combination

JHEP 11 (2015) 206

**Run-I only**

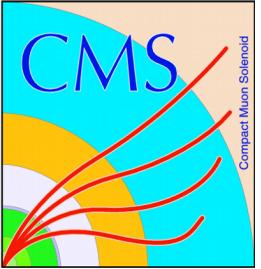
	Upper limit on BR(H $\rightarrow$ inv)	
	Obs.	Exp.
VBF	0.28	0.31
VH, V $\rightarrow$ JJ	0.78	0.86
VH, V $\rightarrow$ $\ell\ell$	0.75	0.62
<b>Combined</b>	<b>0.25</b>	<b>0.27</b>

Sensitivity dominated by VBF search



- A statistical combination of the H $\rightarrow$ invisible direct and indirect search, from the coupling parametrisation

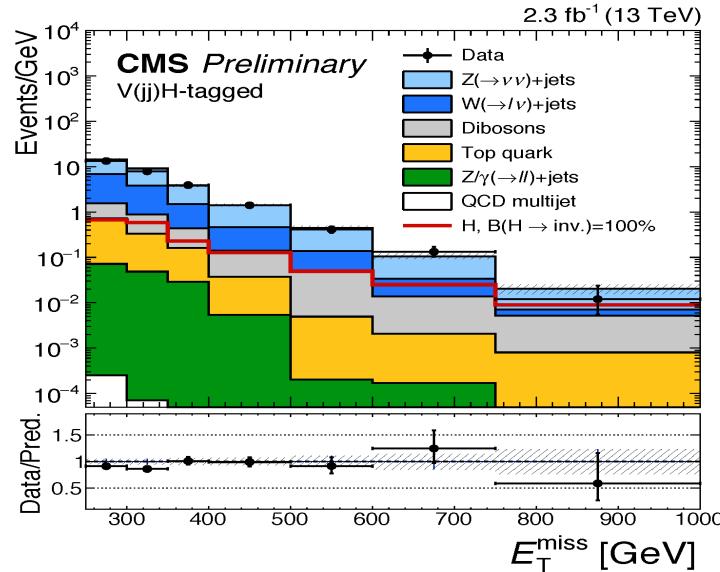
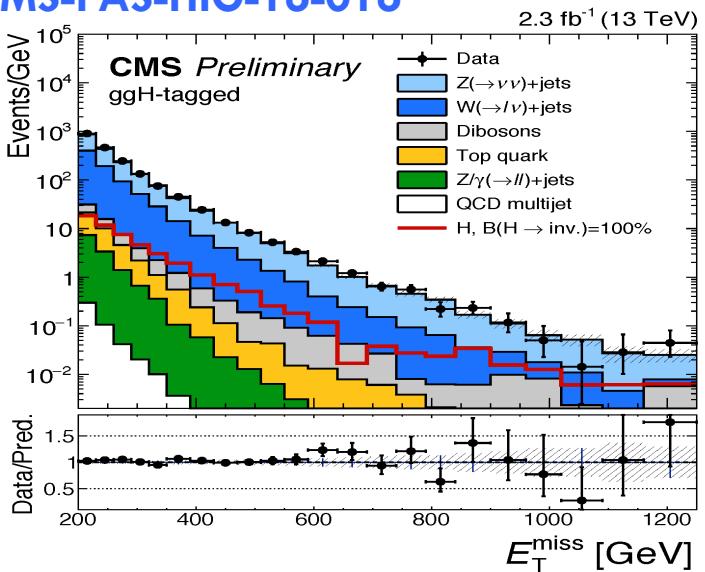
Decay channels	Coupling parameterisation	$\kappa_i$ assumption	Upper limit on BR <sub>inv</sub>	
			Obs.	Exp.
Invisible decays	[ $K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}$ ]	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	[ $K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}$ ]	$\kappa_{W,Z} \leq 1$	0.49	0.48
<b>Inv. &amp; vis. decays</b>	<b>[<math>K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}</math>]</b>	<b>None</b>	<b>0.23</b>	<b>0.24</b>
Inv. & vis. decays	[ $K_W, K_Z, K_t, K_b, K_\tau, K_\mu, K_g, K_\gamma, K_{Z\gamma}, \text{BR}_{\text{inv}}$ ]	$\kappa_{W,Z} \leq 1$	0.23	0.23



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# $H \rightarrow \text{invisible}$ : ggF and V(jj)H in CMS

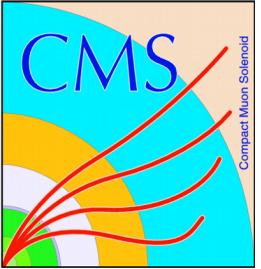
CMS-PAS-HIG-16-016



**NEW with 12.9  $\text{fb}^{-1}$**

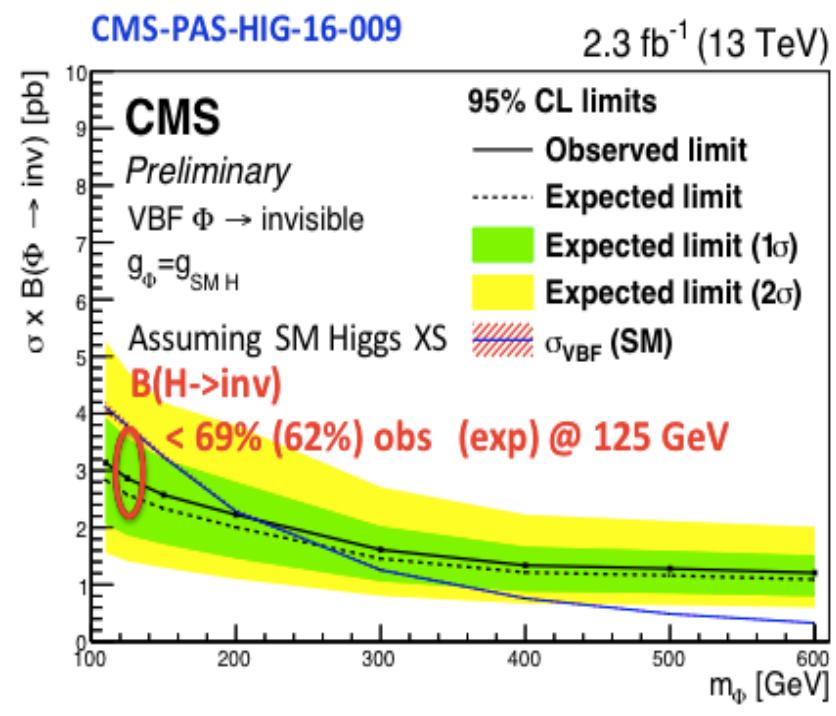
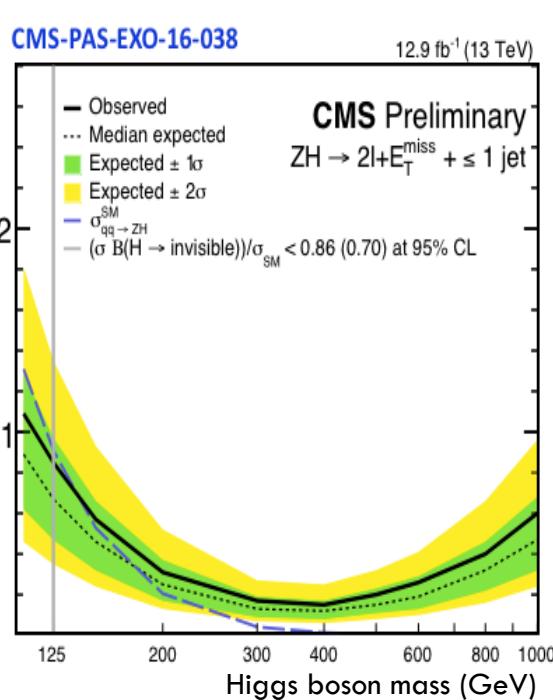
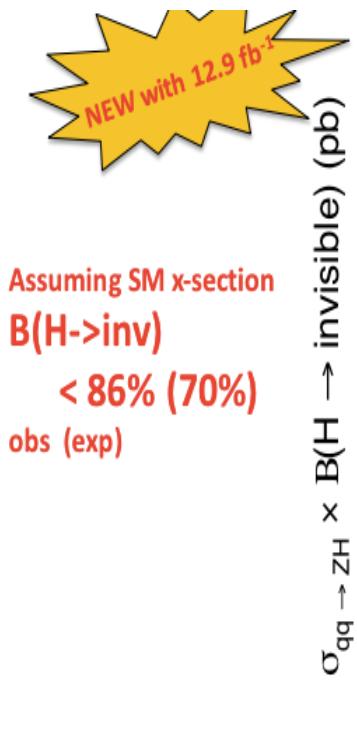
**CMS-PAS-EXO-16-037**

	Expected	Observed
ggH - tag	0.85	<b>0.48</b>
V(jj) H -tag	0.72	<b>1.17</b>
Comb.	0.56	<b>0.44</b>



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# $H \rightarrow \text{invisible}$ : $Z(l\bar{l})H$ and VBF in CMS



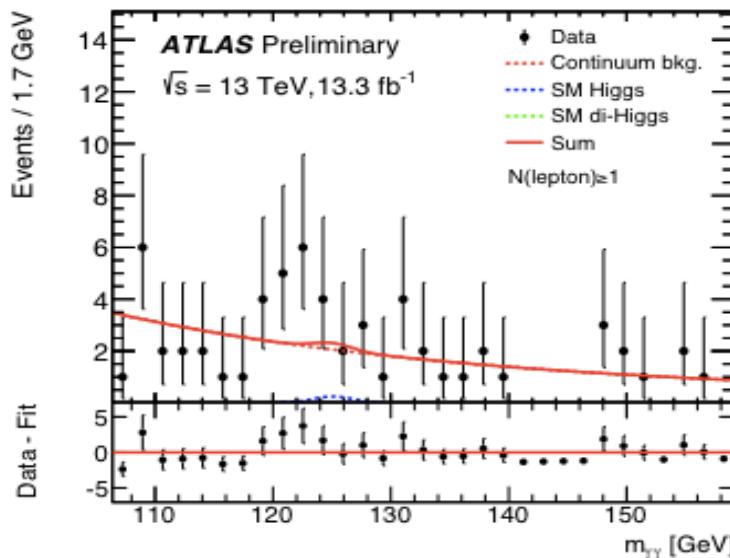
# Non-resonant di-higgs in ATLAS at 13TeV

[ATLAS-CONF-2016-071](#)

## $hh \rightarrow \gamma\gamma WW^*$

- Final state:  $\gamma\gamma lvqq$
- Events with two photons, at least two jets and no bjets

Non-resonant Search:  
 $\sigma(pp \rightarrow hh) < 25.0 \text{ pb}$   
 (expected limit = 12.9 pb)

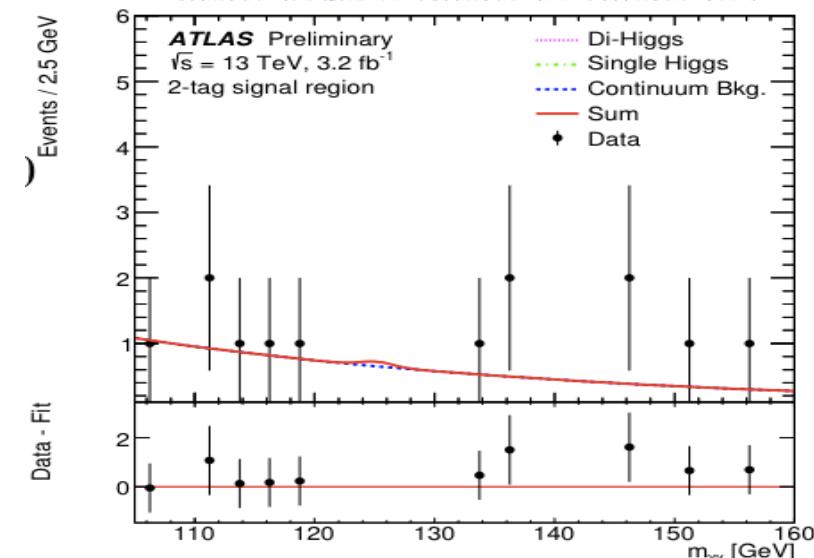


[\(ATLAS-CONF-2016-004\)](#)

## $hh \rightarrow bb\gamma\gamma$

- Follow  $h \rightarrow \gamma\gamma$  analysis section
- Events with 2 bjets,  $95 \text{ GeV} < M_{bb} < 135 \text{ GeV}$

Non-resonant Search:  
 $\sigma(pp \rightarrow hh) < 3.9 \text{ pb}$  with SM BR  
 (expected limit = 5.4 pb)



# Non-resonant : $hh \rightarrow bbbb$ in ATLAS

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ATLAS-CONF-2016-049

13TeV: 13.3  $\text{fb}^{-1}$

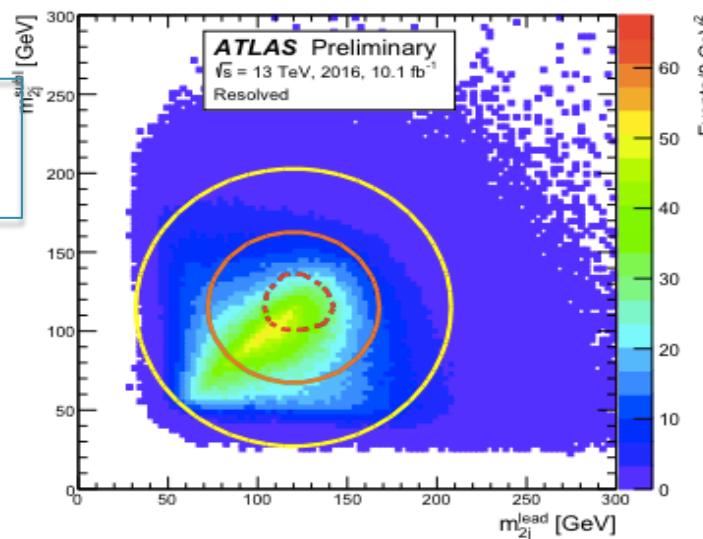
## Non-resonant Search:

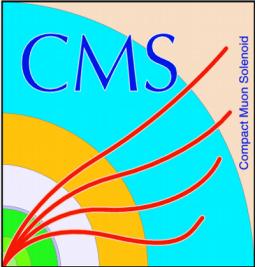
Only in resolved analysis  
 $\sigma(pp \rightarrow hh \rightarrow bbbb) < 330 \text{ fb}$   
 (SM prediction = 11.3 fb)

$\sigma(pp \rightarrow hh) < 0.98 \text{ pb}$   
 with SM BR

RESOLVED

Sample	2015 Signal Region	2016 Signal Region
Multijet	$1131 \pm 68$	$3670 \pm 200$
$t\bar{t}$	$57 \pm 34$	$190 \pm 110$
Total	$1189 \pm 76$	$3860 \pm 230$
Data	1231	3990





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# Non-resonant di-higgs in CMS

[bb \$\gamma\gamma\$ :arxiv:1603.06896](#); bbWW: CMS-PAS-HIG-16-024; bb $\tau\tau$ : CMS-PAS-HIG-16-028

- ❑ AT least one  $h \rightarrow b\bar{b}$  to have large BR
- ❑ RUN2 datasets have been probed in bbWW and  $bb\tau\tau$  analysis.
- ❑ No accesses observed in these channels.
- ❑ At the moment, we can probe  $O(10-100 \times \text{SM})$ .

Non-resonant production exclusion			
bbWW	$410 \times \sigma(\text{SM})$		13TeV 2.3 fb $^{-1}$
bb $\tau\tau$	$200 \times \sigma(\text{SM})$		13TeV 12.9 fb $^{-1}$
bb $\gamma\gamma$	$74 \times \sigma(\text{SM})$ (RunI)		

# Summary

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- Searches for LFV, NMSSM and  $H \rightarrow$ invisible decays have been reported in this talk, as well as non-resonant di-higgs results, from ATLAS and CMS with RUN1 and RUN2 datasets
- No excesses have been observed so far.
- More data is needed to further constrain the potential models and reveal possible physics of BSM – RUN2 or even RUN3